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16. ABSTRACT

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YIELD RESPONSE CURVES OF CROPS EXPOSED TO SO_2 TIME SERIES

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Abstract—Six species (alfalfa, onion, lettuce, radish, red clover, Douglas fir) were exposed in field growth chambers to both constant concentration and stochastic SO_2 time series. Yield response curves were generated with median concentrations ranging from 0 to 20 pphm. Constant concentration treatments were found to underestimate yield loss compared with the pollutant time series treatments. An heuristic model of plant assimilation of SO_2 is presented to explain this result.

INTRODUCTION

Vegetation growing near a source of SO_2 experiences a randomly varying sequence of pollutant concentrations. This probabilistic nature of pollutant concentrations can be characterized with a time series model (Male, 1982). To predict yield loss caused by SO_2 pollution one can relate plant response to characteristics of natural pollutant time series.

If plant yield depends only upon the amount of SO_2 absorbed during a growing season, then it will be insensitive to the temporal dynamics of a time series. In this case, a constant concentration exposure regime will be equivalent to a natural time series having the same mean value. This assumption is the basis for extrapolating the results of fixed concentration and arbitrarily varied concentration experiments to predict yield loss of plants exposed to natural pollutant time series. If this assumption is correct, then the total amount of SO_2, irrespective of the temporal dynamics of pollutant concentration will be the determinant of yield. However, both pollutant concentration and exposure duration are important determinants of vegetation response. Plants respond differently to identical doses (concentration × time) administered in different combinations of exposure time and pollutant concentration. At equivalent doses, plant damage increases rapidly with increasing concentration and decreasing exposure time (van Haut, 1961; Larsen and Heck, 1976; McLaughlin *et al.*, 1979). Plant response to SO_2 also varies with environmental conditions before, during, and following exposure; time of day; and stage of plant development (see reviews: Daines, 1968; Guderian, 1977; NAS, 1978; Linzon, 1978; Ziegler, 1975).

Plant yield (biomass) is the integral over a growing season of the growth rate. Growth rate is a stochastic time series depending upon environmental conditions, including pollutant concentration. If the probabilistic relationship between yield and a summary statistic for a pollutant time series were known, then knowledge of a pollutant's probability distribution would allow one to predict the probability distribution of yield.

Because plant yield may be highly dependent on the temporal dynamics of pollutant concentrations, experiments designed to characterize yield response should employ realistically fluctuating pollutant exposures. At least three experimental methods have been developed to achieve this. Oshima *et al.* (1976) conducted growth experiments based on environmental gradient analysis. Preston and Lee (1982) and Miller *et al.* (1980) utilized the zonal air pollution system (ZAPS) to produce realistic short-term fluctuations in concentration. The National Crop Loss Assessment Network (NCLAN) (Heck *et al.*, 1982) utilizes open-top chambers (Heagle *et al.*, 1973) to expose field grown plants to increments above measured ambient pollutant levels, creating a realistic exposure time series. A drawback of all three methods is that treated plants receive only one of an infinite number of possible time series. Replication of time series is required to estimate the mean response to a given time series model.

The experimental approach described here obviates the above problem. Plants are grown in pots and each pot experiences a different time series exposure. Individual pot yields are averaged to estimate the mean yield over all possible time series having the same median concentration. The distribution of yield is still influenced by environmental conditions during the experiment, but variability attributable to time series has been accounted for.

The hourly concentrations from an SO_2 time series are lognormally distributed and a sufficient characterization for this distribution is the parameter triplet consisting of the median, shape parameter and correlation. The model used for exposure regimes was a first-order, autoregressive, stochastic process which generated lognormally distributed concentrations with realistic correlation structure (Male, 1982).

Male (1982) describes an experimental design based on this SO_2 time series model for estimating yield

response curves in field growth chambers. In this paper we demonstrate this exposure methodology by estimating yield response curves for six species and contrast the results with yields from comparable fixed concentration treatments.

METHODS AND MATERIALS

Approximately 200 pots for each of six species were exposed to simulated time series of SO_2 concentrations. Each pot for a given species experienced a different stochastic time series with the same correlation (0.9) and shape parameter (0.89) (Male, 1982). A different time series, the length of a growing season, was generated for each of 12 field growth chambers. A gradient in median concentration across the 12 chambers, combined with weekly movement of pots among chambers, allowed the range of medians for individual pot time series to extend from 0 to 21 pphm (Male, 1982). The concentration was manually adjusted each hour within each chamber. Four chambers in 1976 (0, 5, 10, 14 pphm) and three in 1977 (0, 12, 18 pphm) were dedicated to fixed concentration treatments. Pots were not moved among the fixed concentration chambers but the possible irritation of physical transportation was duplicated by moving the pots in and out of their respective chambers.

Species for the study were chosen using the following criteria: plants of a size that could be grown in a 20 cm pot; plants representative of root, leaf, forage and timber crops; plants that could be grown in local climate.

The following species were selected: Alfalfa, *Medicago sativa* L. var. Mesa-Sirca; Onion, *Allium cepa* L. var. Sweet Spanish Yellow; Lettuce, *Latuca sativa* L. var. Buttercrunch; Radish, *Raphanus sativus* L. cv. Cherry Belle; Red Clover, *Trifoleum pratence* L. var. Kenland; Douglas fir, *Pseudotsuga menziesii* (Mirb.) Franco.

Douglas fir were planted as 1-year-old seedlings. Other plants were seeded in a 75% clay loam and 25% Jiffy-Mix-Plus mixture in 6-ℓ (21.6-cm diameter) plastic pots. Amendments mixed into the soil prior to seeding were 2.3 kg m^{-3} of 11-33-11-5 (N, P, K, S) and 1.2 kg m^3 hydrated lime. The soil was not sterilized. Seeds were planted in soil at a depth equal to approximately three times their diameter. The number of plants per pot varied with species characteristics.

To prevent soil moisture stress, plants were watered as necessary to water holding capacity using weighted feeder lines from a drip irrigation system. Onions received two additional fertilizations with a solution of $CaNO_3$ at a rate of 44 kg m^{-2}. No herbicides were used. Insecticides were used when insects were found in sufficient numbers to threaten the study.

Yield measurements, based upon marketable portion, were

Table 1. Frequency, mean and standard deviation of yield within SO_2 groupings by species and type of treatment (stochastic vs constant). Exposure dates

		Stochastic SO_2						Constant SO_2			
Radish 1976	Median SO_2 (pphm)	$c < 3$	$3 \leqslant c < 5$	$5 \leqslant c < 8$	$8 \leqslant c < 12$	$12 \leqslant c < 16$	$16 \leqslant c$	0	6	10	14
6/17	Frequency	54	79	72	69	51	41	30	35	33	35
to	Mean (g)	5.1	4.9	4.5	3.2	3.1	2.2	4.0	4.9	4.6	4.6
7/12	Std. dev.	1.5	1.6	1.6	1.7	1.6	1.7	1.6	1.8	1.7	1.6
Lettuce 1976	Median SO_2 (pphm)	$c < 3$	$3 \leqslant c < 5$	$5 \leqslant c < 8$	$8 \leqslant c < 12$	$12 \leqslant c < 16$	$16 \leqslant c$	0	6	10	14
6/17	Frequency	56	68	93	42	80	25	33	33	32	35
to	Mean (g)	26.1	25.5	21.2	21.2	20.6	17.7	21.1	23.3	22.3	20.3
7/29	Std. dev.	4.2	4.2	4.0	5.5	4.8	4.9	4.2	4.4	4.2	4.5
Onion 1977	Median SO_2 (pphm)	$c < 3$	$3 \leqslant c < 5$	$5 \leqslant c < 8$	$8 \leqslant c < 12$	$12 \leqslant c < 17$	$17 \leqslant c$	0	12	18	
6/14	Frequency	29	37	43	33	37	13	16	16	16	
to	Mean (g)	16.9	15.8	12.1	8.0	3.9	0.9	13.5	12.6	9.0	
9/20	Std. dev.	6.4	3.8	4.2	4.2	3.5	1.0	2.9	4.0	3.0	
Lettuce 1977	Median SO_2 (pphm)	$c < 3$	$3 \leqslant c < 5$	$5 \leqslant c < 8$	$8 \leqslant c < 12$	$12 \leqslant c < 17$	$17 \leqslant c$	0	12	18	
6/14	Frequency	27	37	42	33	37	13	16	16	16	
to	Mean (g)	11.9	12.2	11.0	10.5	9.1	7.0	12.4	10.9	12.4	
7/25	Std. dev.	2.4	1.6	1.6	2.1	2.5	2.2	1.3	1.5	1.3	
Doug. fir 1977	Median SO_2 (pphm)	$c < 3$	$3 \leqslant c < 5$	$5 \leqslant c < 8$	$8 \leqslant c < 12$	$12 \leqslant c < 17$	$17 \leqslant c$	0	12	18	
7/19	Frequency	33	35	38	36	38	12	15	16	15	
to	Mean (g)	4.5	4.3	4.2	4.4	3.5	2.4	5.7	4.7	4.6	
9/20	Std. dev.	1.0	0.9	1.1	1.1	1.2	0.7	1.7	1.1	1.2	
Clover 1977	Median SO_2 (pphm)	$c < 3$	$3 \leqslant c < 5$	$5 \leqslant c < 8$	$8 \leqslant c < 12$	$12 \leqslant c < 17$	$17 \leqslant c$	0	12	18	
7/26	Frequency	26	38	41	33	36	14	14	16	13	
to	Mean (g)	6.7	5.5	5.0	3.7	1.5	0.7	3.4	3.4	2.3	
9/20	Std. dev.	2.9	2.7	2.4	2.7	1.7	1.2	2.2	1.8	1.8	
Alfalfa 1977	Median SO_2 (pphm)	$c < 3$	$3 \leqslant c < 5$	$5 \leqslant c < 8$	$8 \leqslant c < 12$	$12 \leqslant c < 17$	$17 \leqslant c$	0	12	18	
6/14	Frequency	*	*	*	*	*	*	15	16	16	
to	Mean (g)	26.0	25.0	22.1	17.6	11.7	5.5	23.0	24.6	24.8	
7/12	Std. dev.	*	*	*	*	*	*	2.3	4.2	4.3	

* Calculations unavailable.

from oven-dried (70°C) tissue weights expressed as grams per pot. Alfalfa tops were cut 7.5 cm above the soil line when control plants reached 1/10 bloom stage. Sequential harvests were taken as the new growth reached maturity. Douglas fir was harvested after two months. Other species were harvested at maturity. Exposure dates are given in Table 1.

Plants were grown in square, 11.5 m^3 closed-top chambers (Heagle *et al.*, 1972) but fitted with a blower which exhausted 330 $\ell\,s^{-1}$ through a 20 kg charcoal filter. SO_2 was dispensed in the exposure chambers as described by Heagle *et al.* (1974) and concentrations were controlled in each chamber by turning a calibrated needle valve. The SO_2 analysers were calibrated weekly using a permeation tube calibration technique (US CFR, 1977). The temperature of the SO_2 dispensing box was maintained at 38°C to prevent diurnal trends in SO_2 concentration. The SO_2 was dispensed 24 h a day, 7 days a week according to the hourly concentrations computed from the stochastic model. During an 8-h period at night the SO_2 concentration within each of the 12 stochastic chambers was held constant at the average value of its time series for that period.

RESULTS

A scatter plot of the raw data for radish is included (Fig. 1) to demonstrate the achieved range and density of median SO_2 concentrations. It also illustrates the magnitude of observed variability in the yield. Each point represents the yield from one pot and each pot experienced a different time series of SO_2 concentration. The data appear grouped because median SO_2 was calculated to the nearest pphm.

The experimental results become clearer if the data are grouped with respect to median SO_2 concentration. Grouping intervals can be chosen which minimize differences in frequency between groups. In Table 1, groups are labeled as $c_1 \leqslant c < c_2$; frequency represents the number of time series whose median fell within the interval between c_1 and c_2; and the sample mean and standard deviation summarize the yield of pots whose median SO_2 concentration fell between c_1 and c_2. In Fig. 2, mean yield response to constant SO_2 levels is compared with the mean yield within the median SO_2 groupings. The mean yield for a group is plotted at the midpoint of its median SO_2 range $[(c_1 + c_2)/2]$. The error bars in Fig. 2 represent plus or minus one standard error.

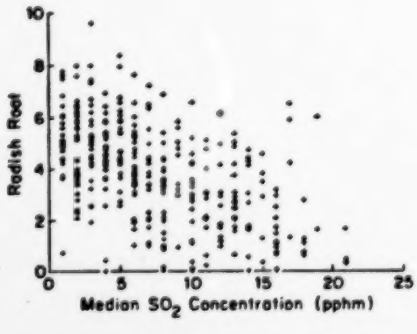

Fig. 1. Scatter diagram—Root dry weight of radish (g) vs median SO_2 concentration (pphm).

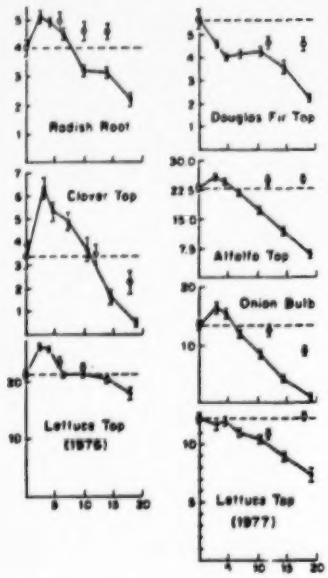

Fig. 2. Mean dry weight (g) vs median SO_2 concentration (pphm). Open circles, constant SO_2; solid circles, stochastic SO_2. Error bars are plus or minus one standard error.

Pot variability was no greater within median SO_2 groups than within fixed concentration experiments. Note, in this regard however, that the standard deviation within a median SO_2 range is biased upward because of the grouping over a range of median SO_2 concentrations. Since each pot within a median SO_2 range experienced a different SO_2 time series, we conclude that variation was due primarily to environmental and ontogenetic effects and that equivalent results would have been obtained with the same number of pots but with fewer different time series. Such an experiment would have been more economical.

SO_2 enhanced the yield at the lower median concentrations for radish, lettuce, onion and clover. This effect has been observed particularly for plants in a sulfur deficient nutrient regime (Thomas *et al.*, 1943; Faller, 1970, 1971; Noggle and Jones, 1979) and is consistent with current models of plant response (Daines, 1968; Guderian, 1977; Ziegler, 1975).

DISCUSSION

The results in Fig. 2 demonstrate that fixed concentration experiments can underestimate yield loss and that this error increases with median SO_2 concentration. This discrepancy can be explained theoretically. On entry, SO_2 dissolves rapidly and is oxidized to

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